

CAAP Quarterly Report

Date of Report: *July 7, 2017*

Contract Number: *DTPH5614HCAP04*

Prepared for: *Arthur Buff, Project Manager, PHMSA/DOT*

Project Title: *Embedded Passive RF Tags towards Intrinsically Locatable Buried Plastic Material*

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For quarterly period ending: *July 10, 2017*

Business and Activity Section

(a) Generated Commitments

Project abstract: Accurate and reliable locating, identifying and characterizing the buried plastic pipes from the ground surface in reducing the likelihood of hit them is critical and imperative to reduce the pipeline incidents. In this collaborative research, a new harmonic radar (frequency doubling) mechanism for smart RF tags design that can detect plastic pipes deeply buried in various soils conditions will be investigated, achieved through efficient tags and highly sensitive readers design, and coupled with intelligent signal processing. The proposed low-cost, small thin-film form passive RF tags can directly be embedded in plastic pipes. It will be able to withstand high temperature processing of plastics and stress involved with horizontal tunneling/drilling of buried pipes. The embedded RF tags have the capability to not only precisely locate the buried plastic pipes, but also have integrated sensing functionality, which can measure the strain-stress changes in the plastic materials. Finally, the vast amount of acquired sensing data from individual tags will be integrated to the advanced signal processing for better data categorization and mining. An innovative prognostics framework for better asset life-cycle management will be developed.

A complete solution is needed that helps in identifying individual buried pipes, their precise location, determining their integrity and sensing for leaks. Buried pipes are expected to have a lifetime of greater than 30 years that are designed to carry a range of liquid and gaseous materials. Among the many pipe technologies, demand for plastic pipes is growing largely because of their low-cost and potential for long life time. Any tags or sensors that are incorporated within these pipes should be able to withstand harsh conditions with a lifetime meeting or exceeding that of the pipes, and should be battery free (passive tag). Furthermore, the overall system should be compact, low-cost, and easy to operate. With advanced techniques to bury the pipes using tunneling approaches it is necessary that tags withstand the associated stress and handling during construction work. Typically, the pipes are buried 3 feet or deeper in the ground and thus the reader should be able to interrogate the tags at these and at higher depths (greater than 5ft is desired).

As summarized in Introduction section, significant advances have been made in the area of electronic tagging of buried objects. However, most of these tags are an afterthought as they are not integral part of the infrastructure. These tags are typically large and are buried along with the objects.

This is simple if open trenching is carried out. However, for plastic pipes that are buried using tunneling this approach will not suffice without making the tags an integral part of the plastic pipe. Furthermore, no RF tags are commercially available that will allow in sensing of the environment and the integrity of the buried object during its life time. Smart RF tag designs are necessary as power harvesting and storage techniques will also have limited life time as the rechargeable batteries (or capacitors) and the associated circuit (e.g., piezo power harvester) will have a limited lifetime. Meanwhile, no advanced data processing algorithms are available for optimally manage and use the vast amount of information embedded into the received RF signals from the proposed new tags. Under this three-year project, the specific technical objectives/goals of the proposed research are:

- 1) Design and development of new passive harmonic radar based smart RF tags with long range detection guided by industry partners;
- 2) Design robust and miniature tags such that they can directly be embedded in plastic pipes during manufacturing;
- 3) Investigate on-tag strain-stress sensing capabilities and efficient data transmission;
- 4) Investigate new massive RFID data mining, processing and classification algorithms with experimental testing;
- 5) Develop a Bayesian Learning based pipeline hazardous prognostics methodology using discrete sensing data;
- 6) Intrinsically locatable pipe materials demonstration and field testing using representative pipe specimens with GPGPU acceleration.

Another equally important objective of this proposed research is to engage MS and PhD students who may later seek careers in this field by exposing them to subject matter common to pipeline safety challenges. Since the project being kicked off, three PhD students from both universities and several MS students have been recruited and trained through this CAAP program and apply their engineering disciplines to pipeline safety and integrity research. The PIs think the educational component is a very important part of the CAAP project and will integrate with research activities with various educational activities to prepare the next generation engineers for gas and pipeline industry. The educational and research impacts sponsored by CAAP has been recognized within the university (see *support letter 3 from Associate Vice Chancellor of university*) and nationally (Two current CAAP-funded students at CU haven been recognized at ASNT annual research symposiums in 2014 and 2015). Specific educational objectives and goals are:

- 1) Guide and train graduate students at University of Colorado-Denver and Michigan State University for the pipe integrity assessment and risk mitigation;
- 2) Integrate with existing mechanisms for undergraduate research at University of Colorado-Denver and Michigan State University for early exposure of pipe industry research to potential engineers;
- 3) Improve the current curriculum teaching at University of Colorado-Denver (ELEC5644 Nondestructive Evaluation and ELEC3817 Engineering Probability and Statistics) and Michigan State University (ECE802-1 Microwave and Millimeter Wave Circuits and ECE802-2 Electronic Systems Packaging) using the achievement from the proposed research;
- 4) Invite pipe industry expert (see support letters later in this proposal) to deliver seminar/workshops to undergraduate/graduate students about the challenges and opportunities in gas and pipeline industry;
- 5) Encourage the involved students to apply internships at DOT and industry to gain practical experiences for the potential technology transfer of the developed methodologies.

The above-mentioned goals and objectives of the proposed Competitive Academic Agreement Program (CAAP) project will be well addressed and supported by the proposed research tasks. Development, demonstrations and potential standardization to ensure the integrity of pipeline facilities

will be carried out with the collaborative effort among different universities and our industry partners. The quality of the research results will be overseen by the PIs and program manager and submitted to high-profile and peer-reviewed journals and leading conferences. The proposed collaborative work provides an excellent environment for integration of research and education as well as tremendous opportunities for two universities supported by this DOT CAAP funding mechanism. The graduate students supported by this CAAP research will be heavily exposed to reliability and engineering design topics for emerging pipeline R&D technologies. The PIs have been actively encouraging students to participate in past and ongoing DOT projects and presented papers at national and international conferences. Students who are not directly participating in the CAAP project will also benefit from the research findings through the undergraduate and graduate courses taught by the PIs and attending university-wide research symposium and workshop, e.g. RaCAS at CU-Denver. The proposed research involves pipeline industry to validate and demonstrate scientific results and quantify engineering principles by working closely with industry partners. They will also collaborate with the CAAP team on this research which may include but is not limited to information exchange, mutual meetings, providing CU and MSU with appropriate technical support for the target application.

(b) Status Update of Past Quarter Activities

Task 1 – On-tag Sensing and Signal Processing

A: Stress Sensor

The polypropylene ferroelectret (PPFE) stress sensor introduced in last quarter report has been further studied for the capacitive dependence on sensor's surface area and a new operating mechanism is also explored for easy integration of sensor with harmonic RFID tag.

The PPFE based stress sensor consist of a thin and porous sheet with two silver electrodes on both sides. The design makes it a lossy capacitor, which changes its characteristics according to the applied load. Calculating the precise change in capacitance is easier in lab environment but there is no direct method that can wirelessly read the capacitance change.

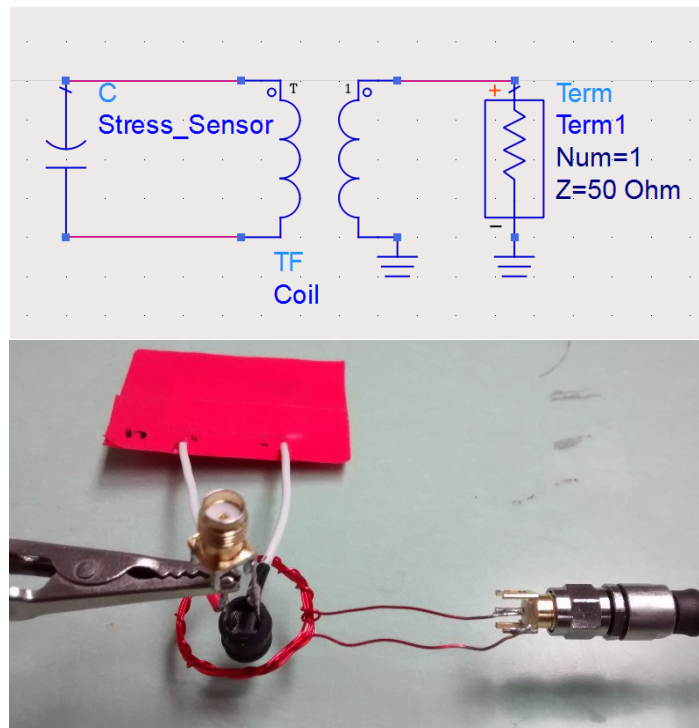


Fig. 1 (a). LC Resonator, (b) Measurement Setup

In order to get the change in capacitance wirelessly, we explored an indirect method that uses an Inductor-Capacitor resonator shown in Fig. 1(a). The inductance in the circuit is kept constant and the variable capacitor is the stress sensor itself. The measurements are made wirelessly using a pickup coil shown in Fig. 1(b) and the initial frequency response of sensor is shown in Fig. 2. High values of inductor and capacitor makes the resonance frequency around 1 MHz. The resonance can be tuned by changing the net inductance of the circuit and can also be increased easily for operating in UHF band with harmonic RFID tag.

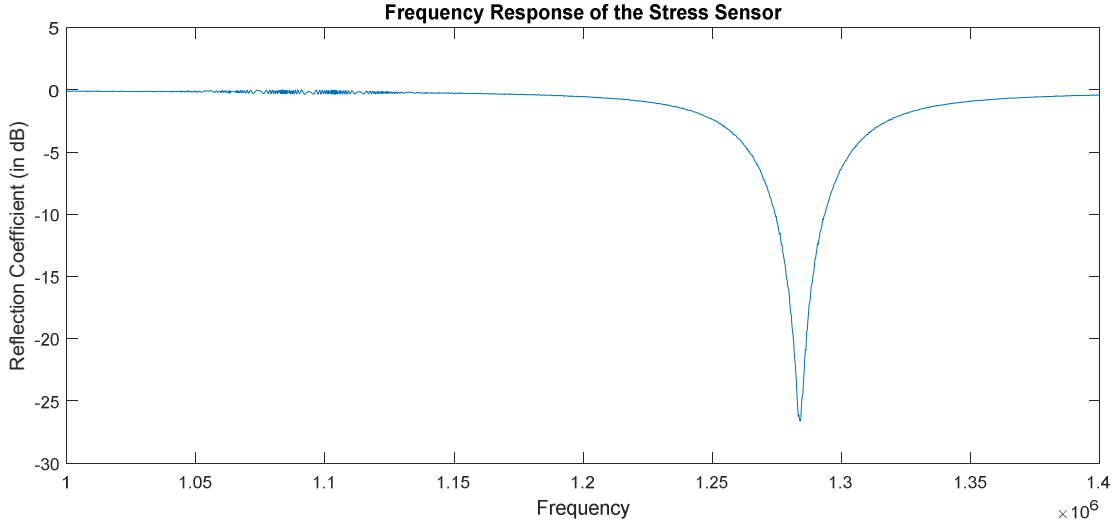


Fig. 2 Frequency Response (No Stress Applied)

With the applied stress, capacitance changes, and so does the resonance shown in Fig. 3. Four metal loads are used to apply stress over the sensor with equal weight and shape. The first metal load makes the significant changes in resonance and shifts it by 36.5 KHz. Additional consecutive loads also shifts the resonance by a linear average of 9 KHz. Comparing these results to the former quarterly report's shows that detecting sensitivity in frequency domain, as opposed to impedance, gives higher net change per unit load, and a clearer linear correlation between changing values.

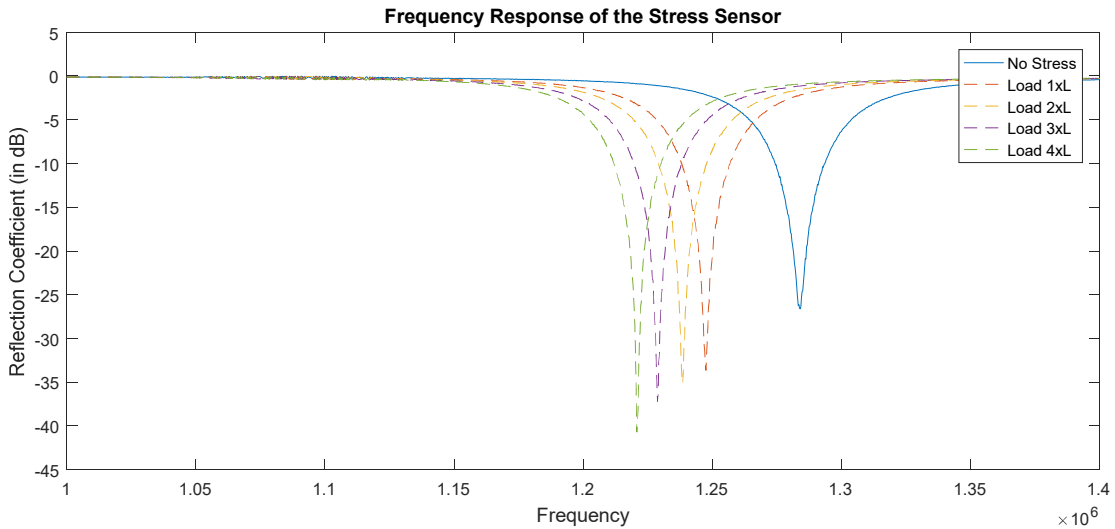


Fig. 3 Resonance Shift due to Applied Stress

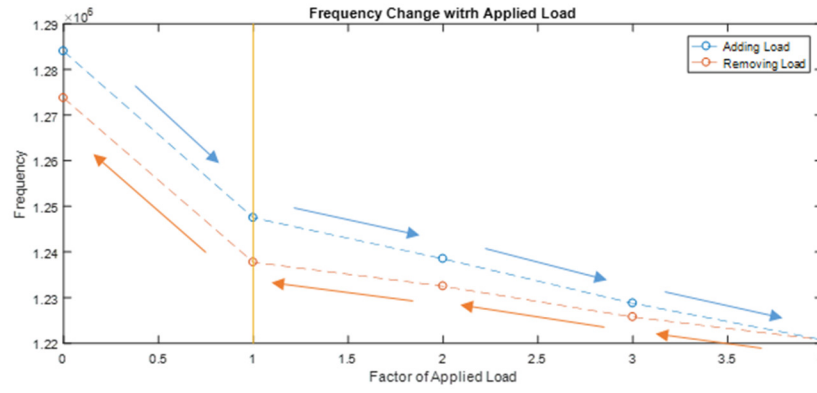


Fig. 4 Resonance frequency

The PPFE stress sensor takes some relaxation time to regain its original shape after pressed by some heavy load. Fig.4 shows the change in resonance while adding load and also while removing it. The net change in capacitance due to four equal loads is linear both ways, but the sensors do not fully regain their shape or capacitance, which leads to different resonance with same applied load.

Many different sizes and shapes of stress sensor shown in Fig. 5(a) have been studied for getting any specific capacitance even with size limitations. Sensor 4 in Fig. 5(a), sensor 4 in Fig. 5(b) and sensor 2 in Fig. 5(c) are all made with the same size of PPFE film, but are organized in different configurations to achieve smaller net surface area by respectively folding and stacking the PPFE. The single layer & folded sensor configurations give relatively the same internal capacitive response, while the stacked sensor capacitance is much larger, due to parallel plate configuration and this pattern is followed by the other sensors shown in Fig. 5.

Table 1. Capacitance control with different configurations

Configuration	Total Area	Impedance @ 15MHz
4x4 [single fold]	16mm ²	43.63
2x2 [folded]	16mm ²	47.39
2x2 [stacked]	16mm ²	210.33
2x4 [single fold]	8mm ²	70.76
2x2 [folded]	8mm ²	67.25
2x2 [stacked]	8mm ²	232.01

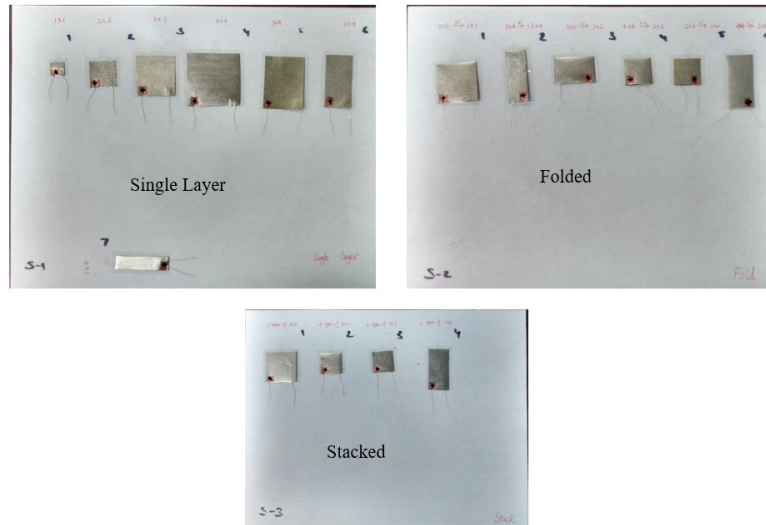


Fig. 5 PPFE Stress Sensors (a) Single Layer, (b) Folded, (c) Stacked

B: Wireless Harmonic RFID System

A new harmonic RFID system (900-1800 MHz) was built to integrate on-tag sensing capabilities, implement depth estimation algorithm, detection of multiple tags, and operating environment, meanwhile a collaborative lab came up with an efficient underground communication system link, so all of these capabilities can be cloned for that system in no time. The experimental setup allowed us to test the harmonic tag operating at 900MHz, which is typical for long-range RFID communication in air.

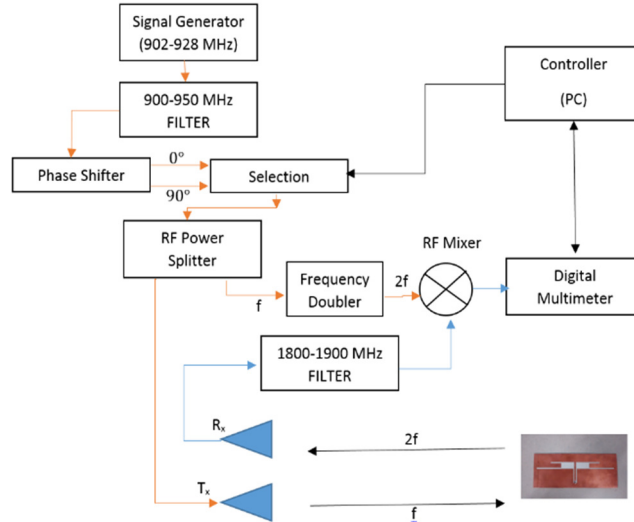


Fig. 6 Block Diagram of Experimental setup for wireless communication

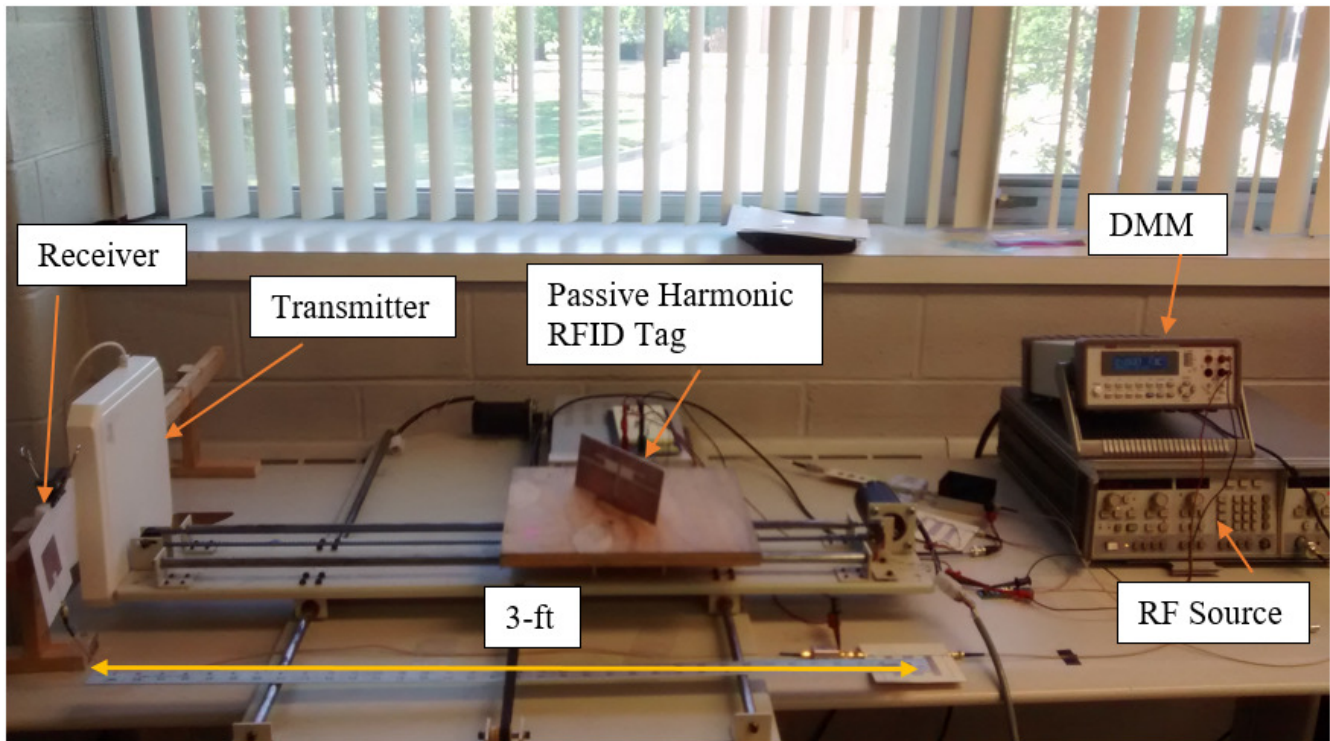


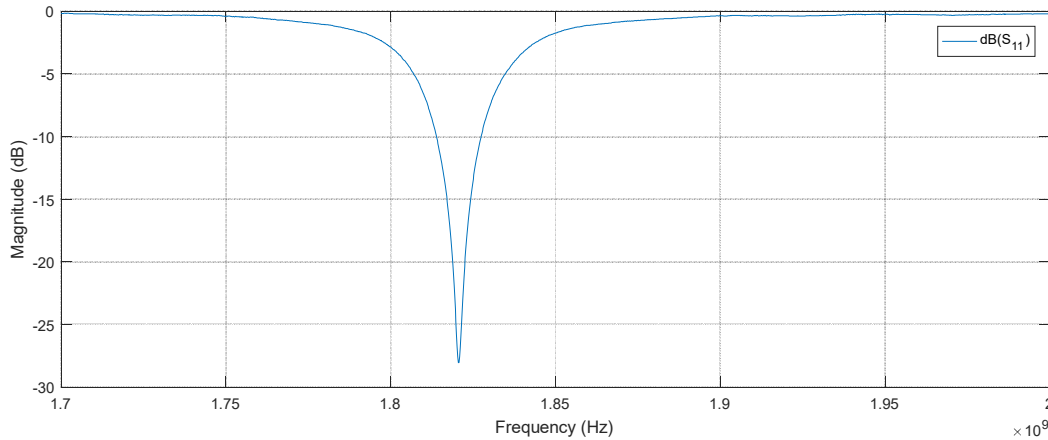
Fig. 7. Experimental Setup

The current setup is able to detect the shown RFID tag up to and including a distance of five feet. The signal strength of received power from the RFID tag at the 1800MHz band is shown in Table 2.

Table 2. Power received by Interrogator

Distance	Signal Strength (dBm)
1- ft	-3.97
2- ft	-5.63
3- ft	-9.42
4- ft	-23.38
5- ft	-29.85

The RFID tag, as well as the receiving antenna, are linearly polarized, meaning maximum signal strength can only be achieved from distance at 0° field of view. The radiating power is set to +16dBm and the circularly polarized antenna from Laird is used to excite the harmonic RFID tag. The receiving antenna is designed to operate in 1800 MHz band. The frequency response is shown in Fig. 8.

**Fig. 8. Frequency Response of Receiver Antenna**

Task 2 – Design and development of passive harmonic radar based smart RF tags

A: Dielectric Property Measurement of Soil

The material properties of the soil decide the amount of power would reach at the tag for underground detection. Hence, it is important to know the material parameters of soil at different frequency and moisture content. In general, as most of the soil is non-magnetic in nature, only dielectric properties of the soil are measured. In this report, the measured results of relative permittivity for typical Michigan soil are shown. Finally, the power budget analysis was performed using the measured dielectric constant.

The sample soil was collected from the backyard of Michigan State University and measured in a coaxial system as shown in Fig. 9. EM2107 coaxial adapter was used to provide a transition from a standard N-type connection to a 51Ω coaxial fixture, which can support TEM mode (no higher order modes) until 1.785 GHz in air medium. The coaxial fixture is capable of S-parameters measurement up to 1 GHz in air medium due to de-embedding constraint. A 3D-printed sample holder was used to place the soil in the coaxial fixture cavity as shown in Fig. 10. Once the sample is inserted, the S-parameters are measured using a network analyzer from 10 MHz to 800 MHz. The coaxial adapter effect was de-embedded using TRL (thru-reflect-line) calibration. After the de-embedding, S-parameters of the sample soil was obtained and Nicholson and Ross algorithm was used to measure the dielectric property of soil. To validate the result, an 11.8 cm long calibration fixture of Plexiglas was measured and compared to the reported data in literature. As expected, the real permittivity is around 2.6 and the imaginary permittivity is close to zero.

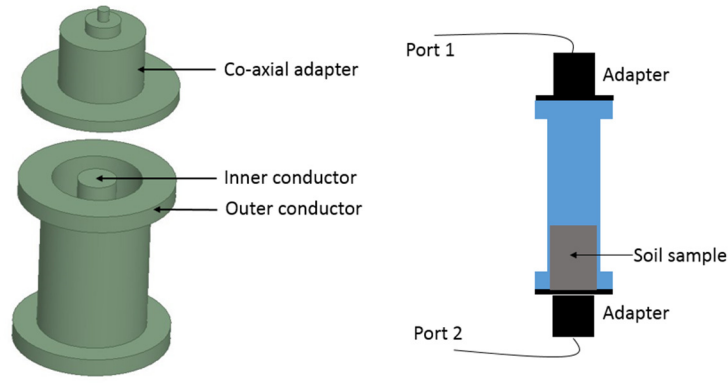


Fig. 9. The Coaxial Cable Setup



Fig. 10. Measurement Setup and Sample Holder

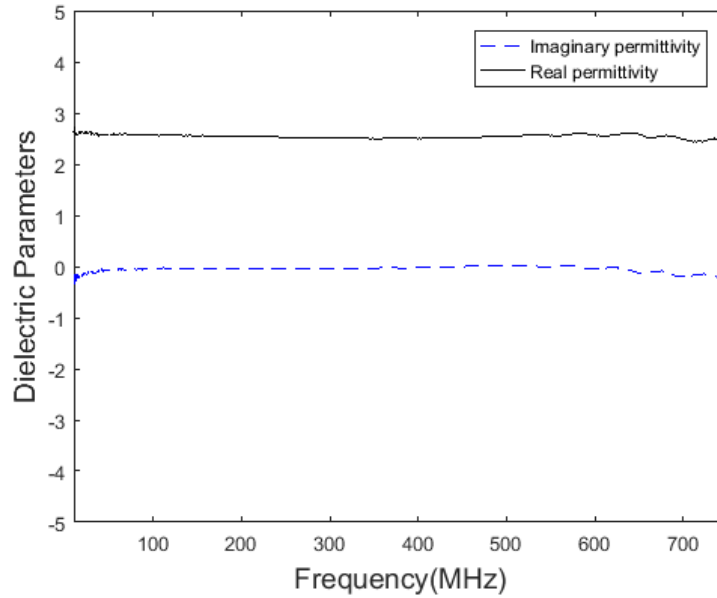


Fig. 11. Extracted value of Real and Imaginary permittivity of Plexiglas

Once the measurement procedure was validated, the data is presented for the Michigan soil at different volumetric moisture content in Fig. 12 and 13. From the results, it can be observed that the real permittivity (ϵ_r) increases with higher moisture content as water has high dielectric constant compared to soil. Also, the soil becomes more lossy with increase in moisture content.

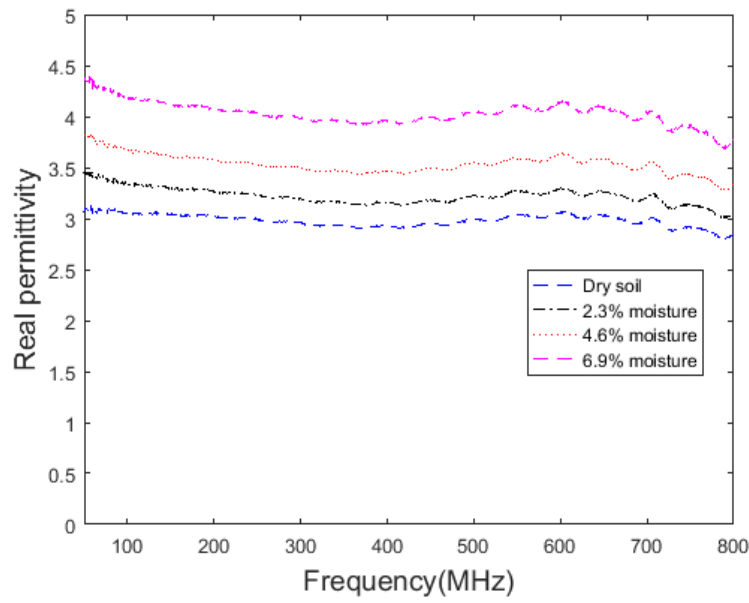


Fig. 12. Extracted values of Real permittivity of soil at a) Dry Conditions, b) 2.3% Volumetric Moisture Content, c) 4.6% Volumetric Moisture Content

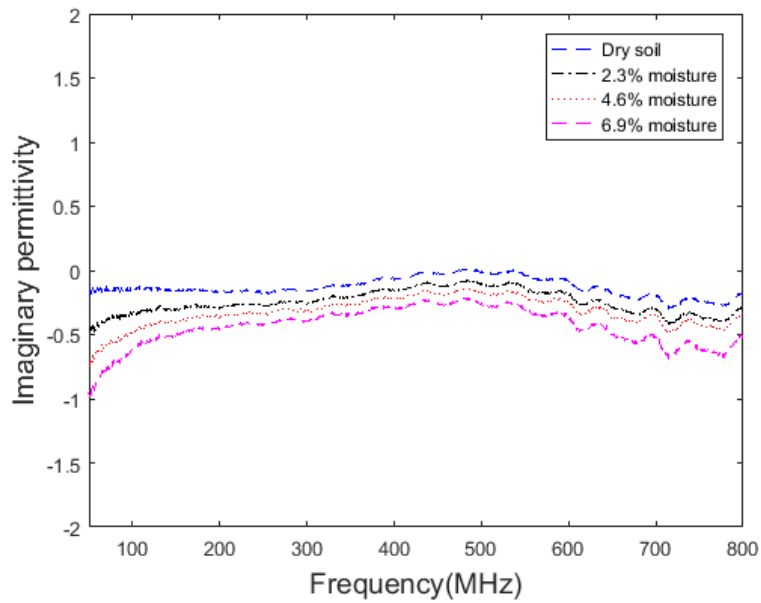


Fig. 13. Extracted values of imaginary permittivity of soil at a) Dry Conditions, b) 2.3% Volumetric Moisture Content, c) 4.6% Volumetric Moisture Content

B: Power Budget Analysis

Path loss analysis was reported earlier in Q5 report for air medium. Similar concept was used and extended for path loss model in soil medium. The Friis formula of received power at a distance d in any lossy dielectric medium is expressed as in (1). The loss factor (α) is given in (2) and the wavelength (λ_s) is to be calculated from (3) where $\lambda_s = 2\pi/\beta$ [Hayt]. The complex relative permittivity of the non-magnetic dielectric is given by ($\epsilon' - j\epsilon''$).

$$P_r = P_t \frac{G_t G_r \lambda_s^2}{(4\pi d)^2} e^{-2\alpha d} \quad (1)$$

$$\alpha = \omega \sqrt{\frac{\mu \epsilon'}{2}} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2} - 1 \right)^{0.5} \quad (2)$$

$$\beta = \omega \sqrt{\frac{\mu \epsilon'}{2}} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2} + 1 \right)^{0.5} \quad (3)$$

After the dielectric properties of soil were determined, the power budget model is developed based on the extracted value. The extracted parameters are provided in table below for different frequencies. Path loss due to attenuation is shown in Fig. 14 for different moisture content in soil sample. With higher moisture content in soil medium, the power loss increases. Also, it can be verified that the soil becomes much lossy at higher frequency. Hence, operation at high frequency is not suitable for underground communication.

Table 3. Dielectric properties used for power budget analysis

Frequency (MHz)	ϵ_r' (Dry)	ϵ_r'' (Dry)	ϵ_r' (2.3% moisture)	ϵ_r'' (2.3% moisture)	ϵ_r' (4.6% moisture)	ϵ_r'' (4.6% moisture)	ϵ_r' (6.9% moisture)	ϵ_r'' (6.9% moisture)
200	3.02	.162	3.27	.282	3.57	.363	4.07	.453
400	2.92	.058	3.15	.147	3.45	.215	3.95	.283
600	3.06	.095	3.29	.194	3.63	.261	4.14	.377
800	2.85	.178	3.07	.299	3.34	.349	3.78	.526

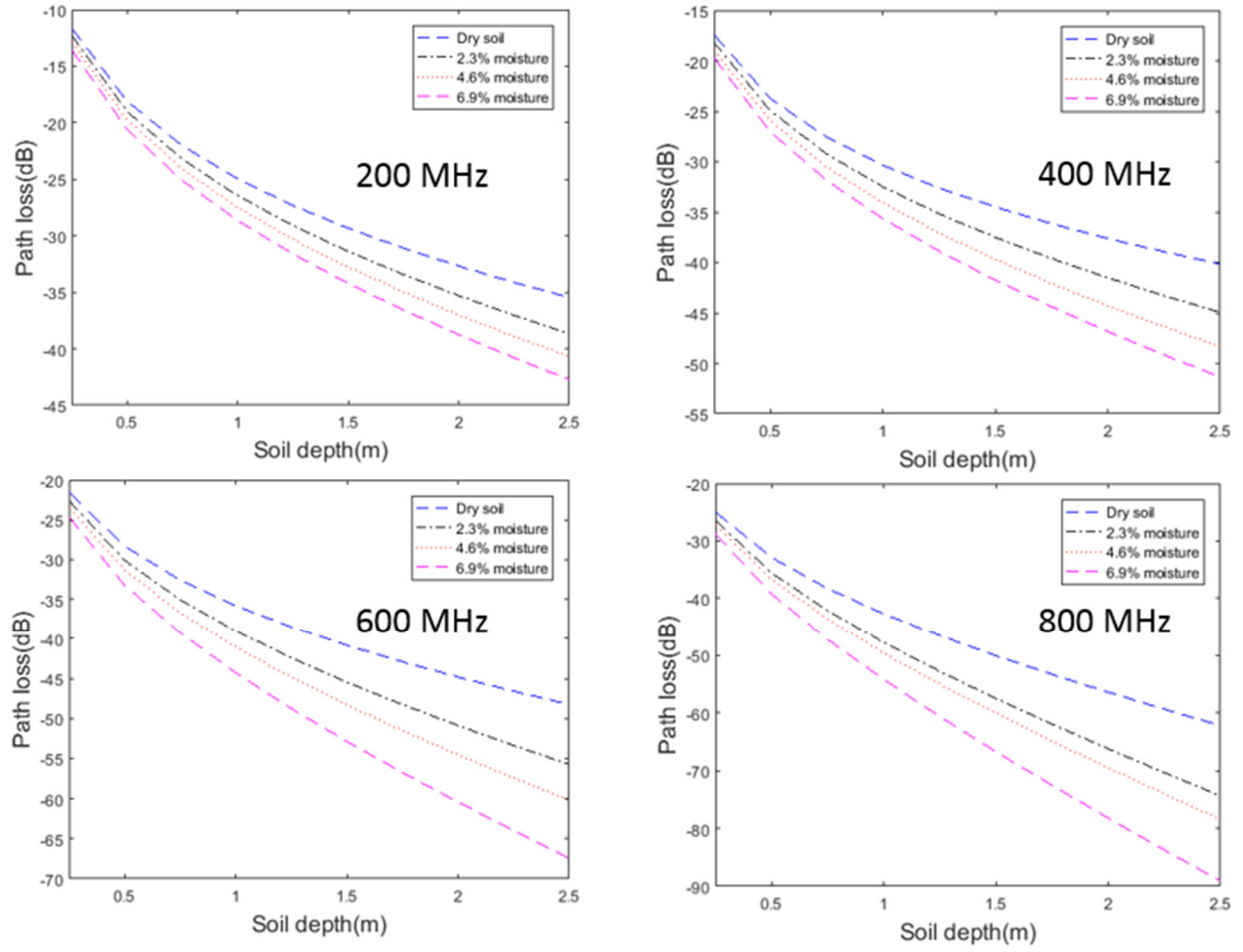


Fig. 14. Path loss in dB at different soil depth for four different frequencies of a) 200 MHz, b) 400 MHz, c) 600 MHz and d) 800 MHz.

C: Antenna Miniaturization

As the operating frequency is lowered, antenna size becomes larger, which would make the harmonic RF tag bulky. Hence, it is required to design small size antenna with reasonable gain. Coil antennas are popular for low frequency operation. A small coil antenna was designed, which is capable of operation along the radial direction. This orientation would be helpful for antenna realization on the pipe itself as shown in Fig. 15. The gain was measured using a VNA at a distance of 5 feet in between the two coils. From VNA measurement, the power loss in air medium was observed as -24 dB. The coil diameter is 17 cm with 8 turns. The region of antenna operation is from 436 MHz to 466 MHz.

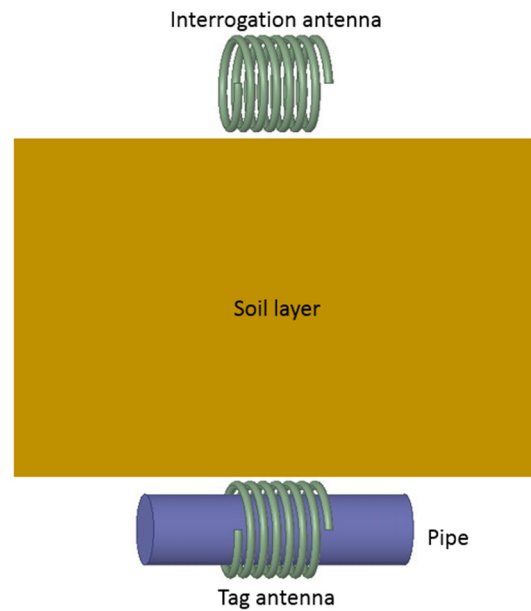


Fig. 15. Diagram of radially wrapped Coil Antenna

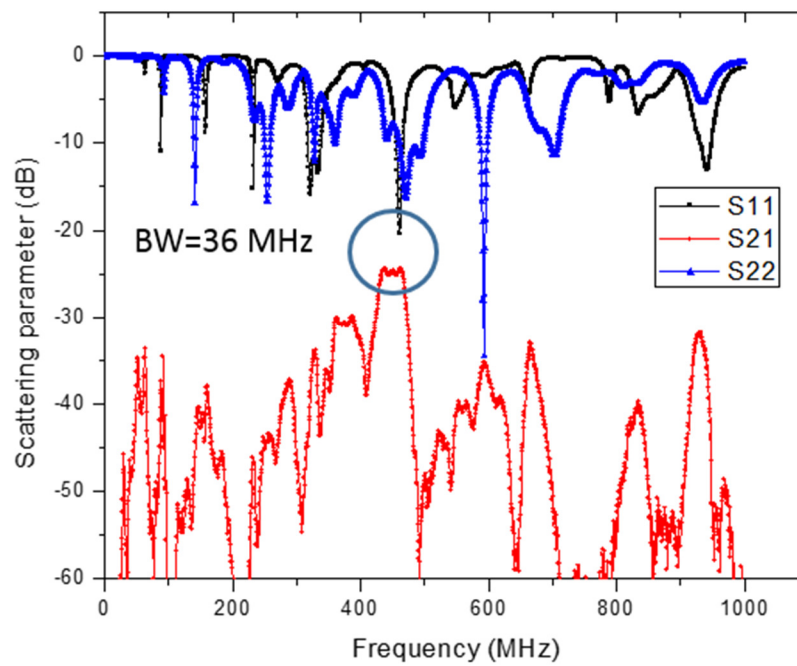


Fig. 16. Measured coil antenna response at 5 feet separation in air

(c) Planned Activities for the Next Quarters

Besides the planned activities mentioned in section (b), here is the future work for the next quarter:

MSU Deng Group: ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:

- Integration of stress sensor with harmonic RFID tag
- Detection of multiple tags
- Distance Estimation of all tags within Antenna field of view

MSU Chahal Group: NEW PASSIVE RFID TAG DESIGN:

- Further improvement on the antenna would be performed.
- The antennas would be integrated with the reader and the tag.
- Measured data would be validated with the power budget analysis.